TRIUMF

DESIGN OF AN INNOVATIVE SUPERCONDUCTING CYCLOTRON FOR COMMERCIAL ISOTOPES PRODUCTION

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On behalf of
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Discovery,
accelerated

Outline

- Motivation
- Major machine parameters
- Conceptual design output
- Challenges
- Look forward

Existing Medical Cyclotrons

There are two main types of commercial medical cyclotrons:

- for medical isotope production
    - high current (0.05–1 mA)
    - low-to-medium energy (7−70 MeV)
    - H^- machines
- for proton therapy
    - low-current (1≤ μA)
    - high-energy (200−400 MeV)
    - proton machines

PET Cyclotrons

Well established:

- IBA: Cyclone 18/9
- ACSI: TR19 => TR24
- GE: PETtrace
- Siemens: Eclipse
- Sumitomo: CYPRIS

Newcomers:

- BEST Cyclotrons
- CIAE: CYCIAE-14
- Compact SC cyclotrons (table-top “coffee makers”)

PT Cyclotrons

Established:

- VARIAN(Germany): ProBeam-250 MeV
- IBA (Belgium): S2C2
- Sumitomo (Japan): P235
- Mevion (USA): S250

Newcomers:

- CIAE (China): CYCIAE-230
- ASIPP, Hefei (China) + Dubna (Russia): SC200 (SC230)

Medical Interest in 100+ MeV Protons

- Ac-225 and Bi-213 : main drivers of radiopharmaceutical developments for treatment of cancers (Melanoma, Prostate and Pancreatic)

- Sr-82 : PET agent in myocardial perfusion imaging

- At-211 and Ra-223 : proven commercial demand

- Ra-224, Pb-212 and Bi-212 : research interest

Cyclotrons in 100 MeV Niche

70−100 MeV range has just taken off the ground:

  - IBA 70 MeV family
  - Best Cyclotrons 70P
  - CYCIAE-100 (Beijing China)

- All are H$^-$ machines.
- Beam losses due to the electromagnetic stripping is a dominant intensity limiting factor.
- Low magnetic field and large magnet size is a compromise to control beam losses at high intensity.

Direction to Alternative Solution

To be efficient and economically attractive:

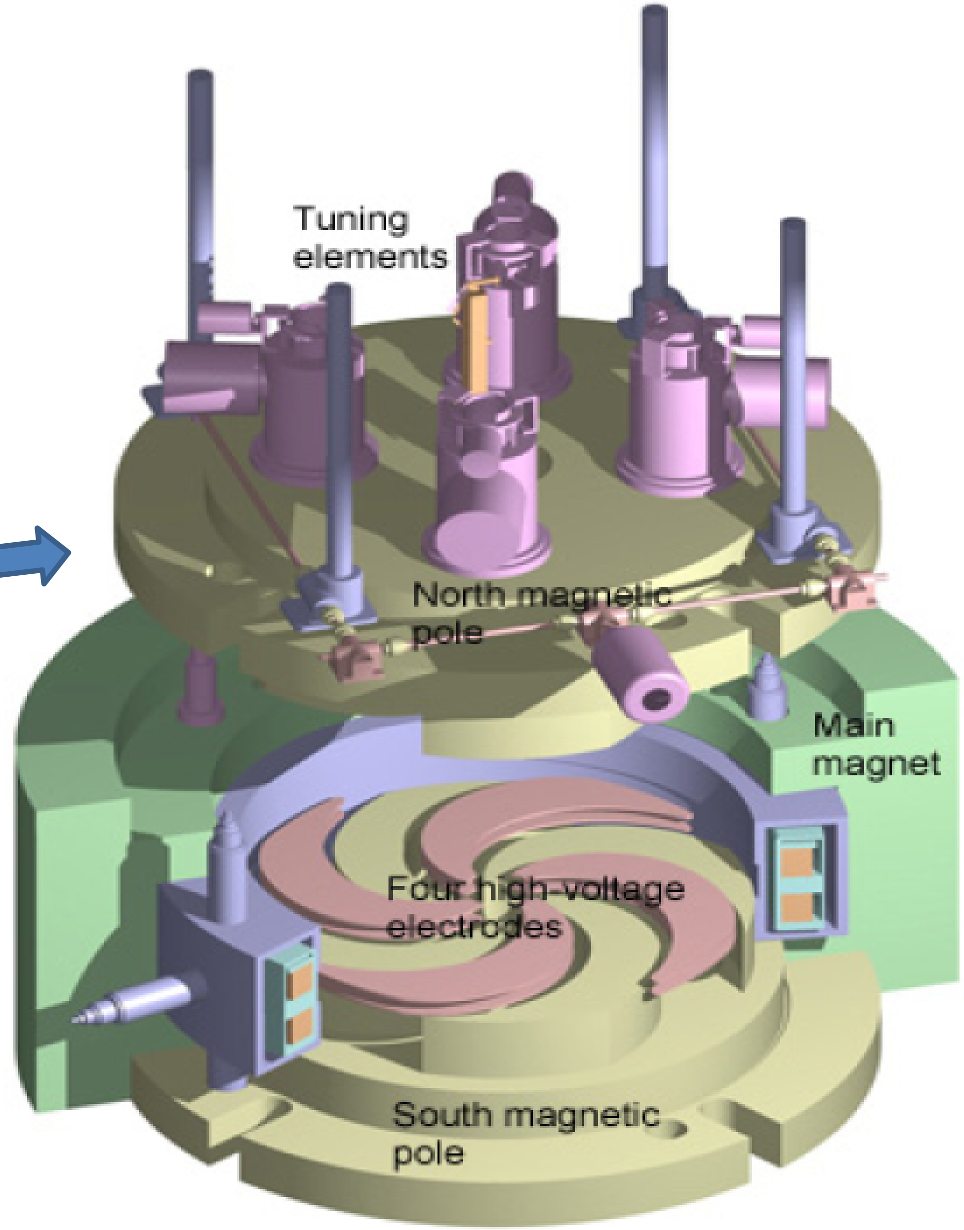
  - Keep machine size small ==> high magnetic field
  - Reduce operating costs ==> superconducting coil

Possible way to go:

- Drop out H^- option ==> switch to H_2^+
  - solve electromagnetic stripping issue (higher binding energy)
  - preserve stripping extraction benefits
  - no need for separated turns
  - preserve large phase acceptance
- Side benefit of S/C magnet: high magnetic field reproducibility and linearity because of iron saturation

Preceding H_2^+ Cyclotron Design Studies

- SCENT project (Catania, Italy)
- IsoDAR/DAEδALUS project (MIT, USA)

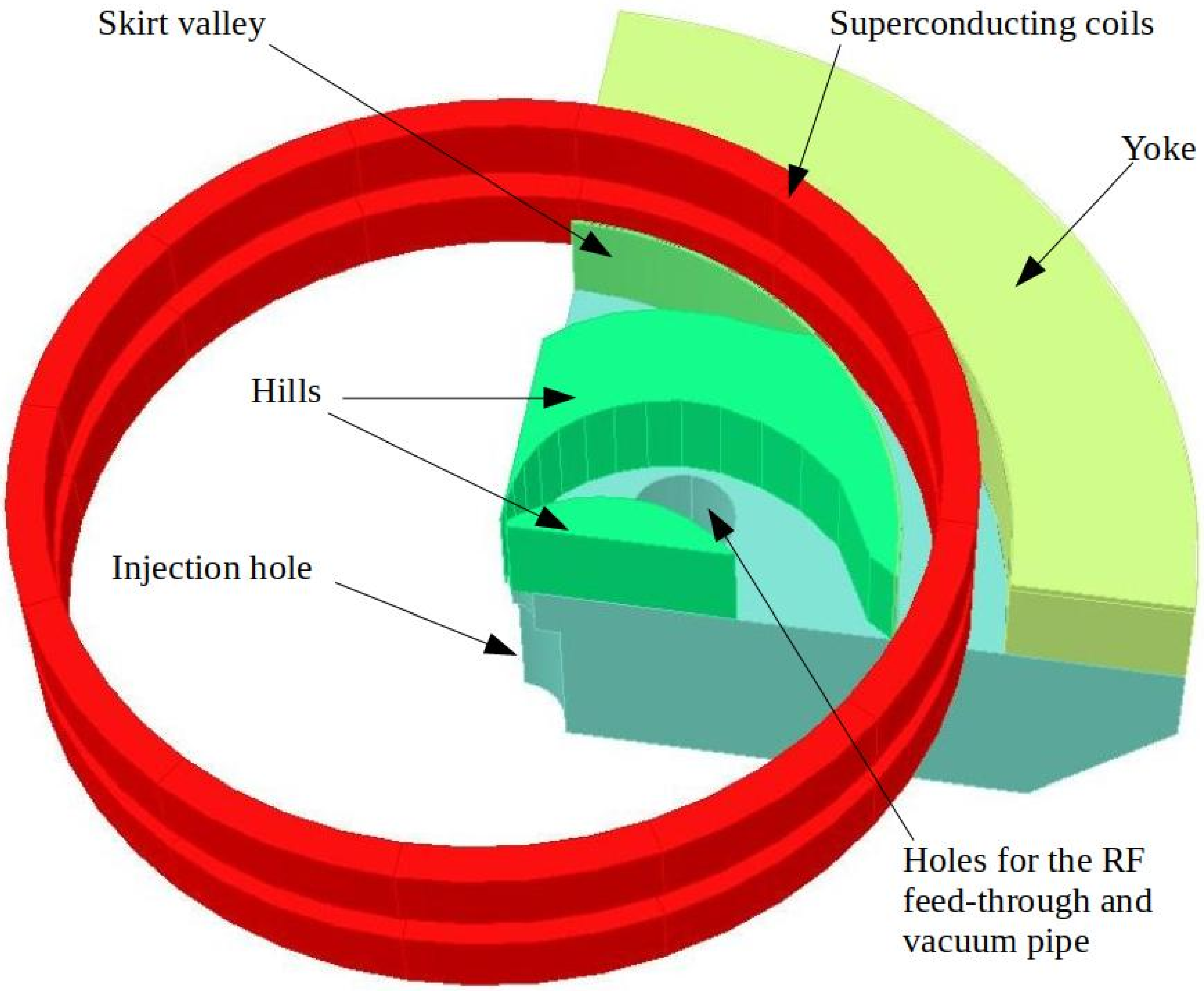


TR100+ Main Parameters

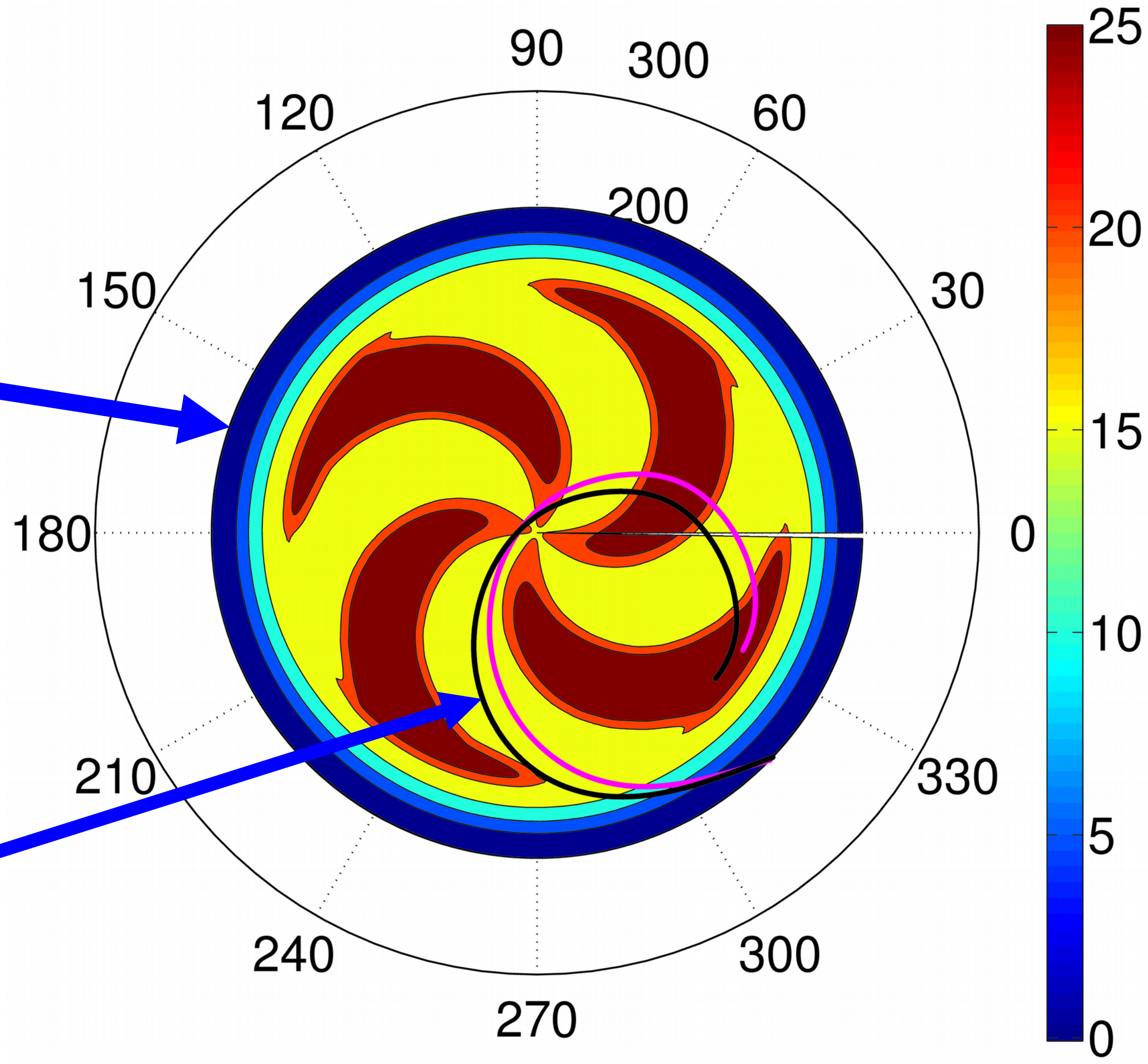
Parameters	**Value**
Particle accelerated	H_2^+
Injection energy (keV)	34.7
Extraction energy (MeV/n)	100−150
Beam intensity (μA)	800
Number of sectors	4
B_0 at centre (T)	2.0
Pole radius (m)	1.65
Injection scheme	Axial + external ion source
Extraction	p by stripping extraction
Coils	2 superconducting coils
Number of RF cavities	2
RF harmonic number	4
RF frequency (MHz)	61
Dee voltage (kV)	69 – 110

OPERA Magnetic Field Model

Parameters	Value
Hill gap (cm)	4.5
Pole radius (cm)	165
Sector azimuthal width (deg)	40 – 46
Sector spiral angle (deg)	20 – 70
Mean magnetic field (T)	2.0 – 2.3
Max. magnetic field (T)	2.5
Max. current density (A/mm²)	30



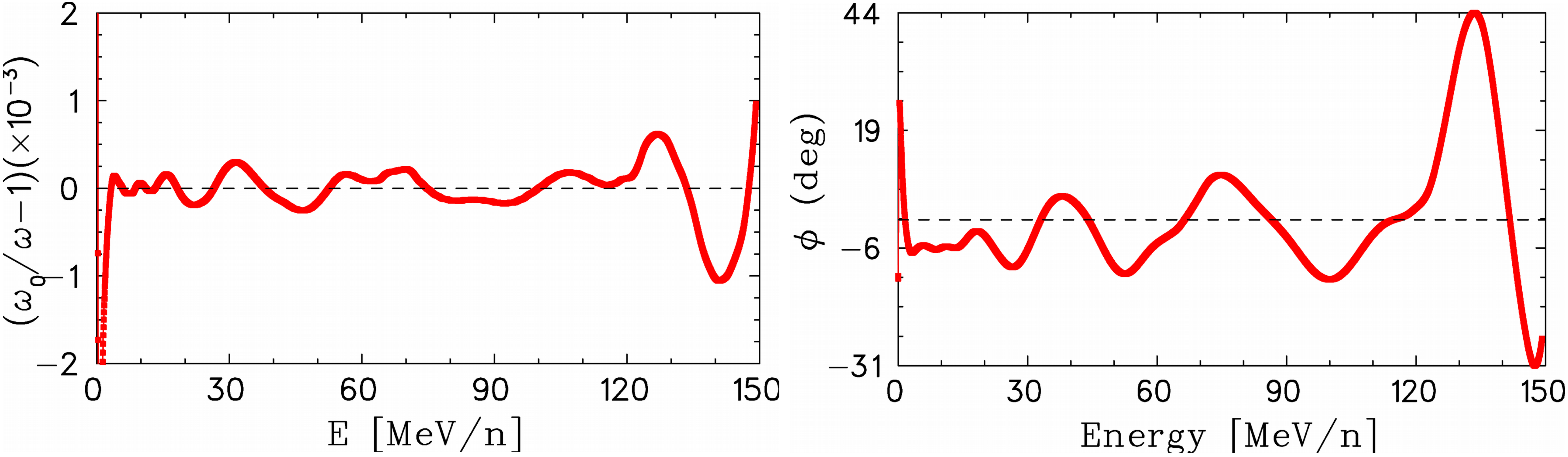
Magnetic Flux Density, Extraction Trajectories



$B_z(r, \theta)$ contour in the median plane (kG)

Extraction trajectories of 150MeV (magenta) and 140MeV (black) protons after stripping (example)

Isochronism & Phase History



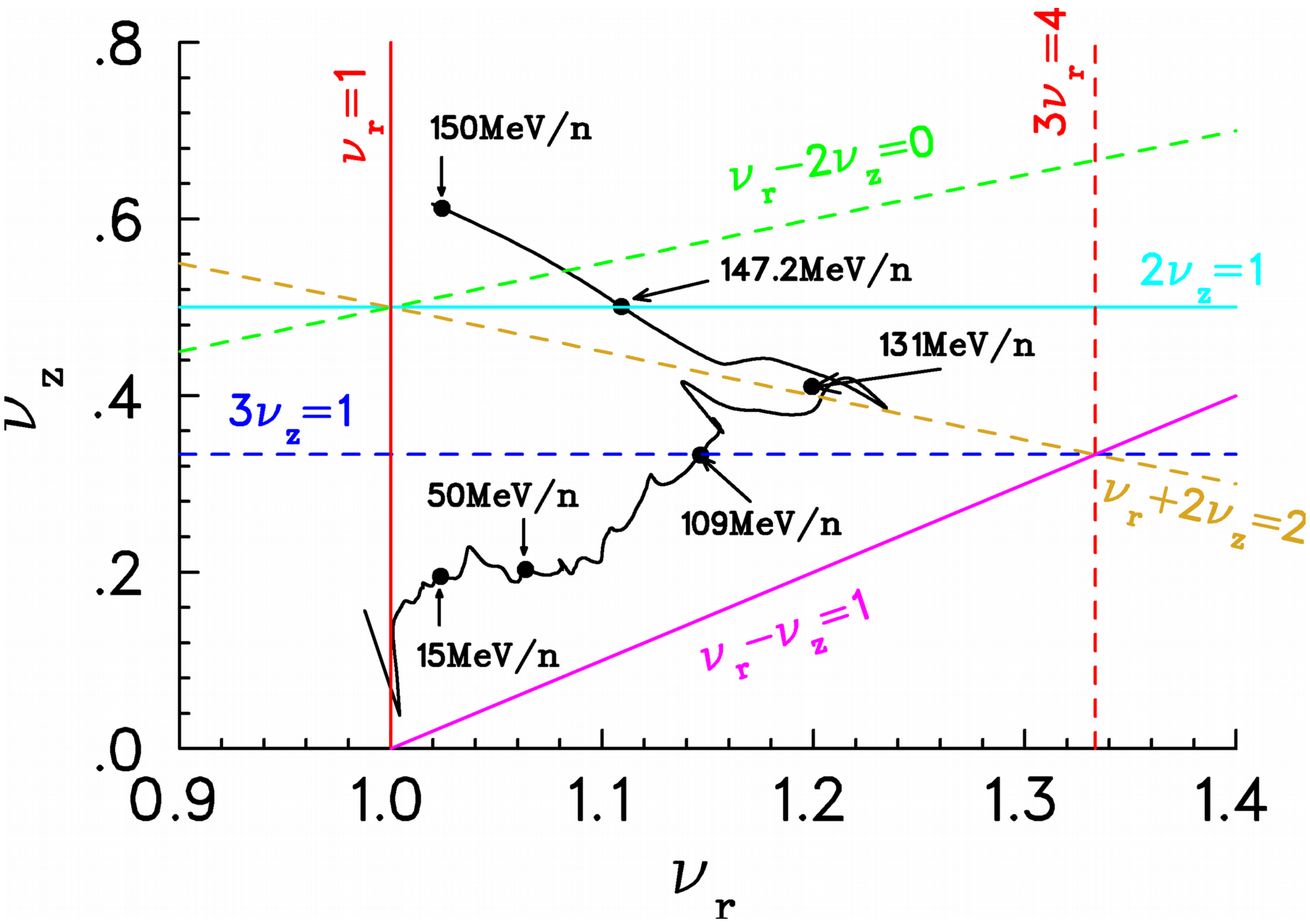
The isochronism parameter is within ±5x10^{-4} over the entire energy range except for the centre region and the extraction region.

The rf phase excursion starys within ±44^{o} for a peak energy gain of 0.4 MeV/turn.

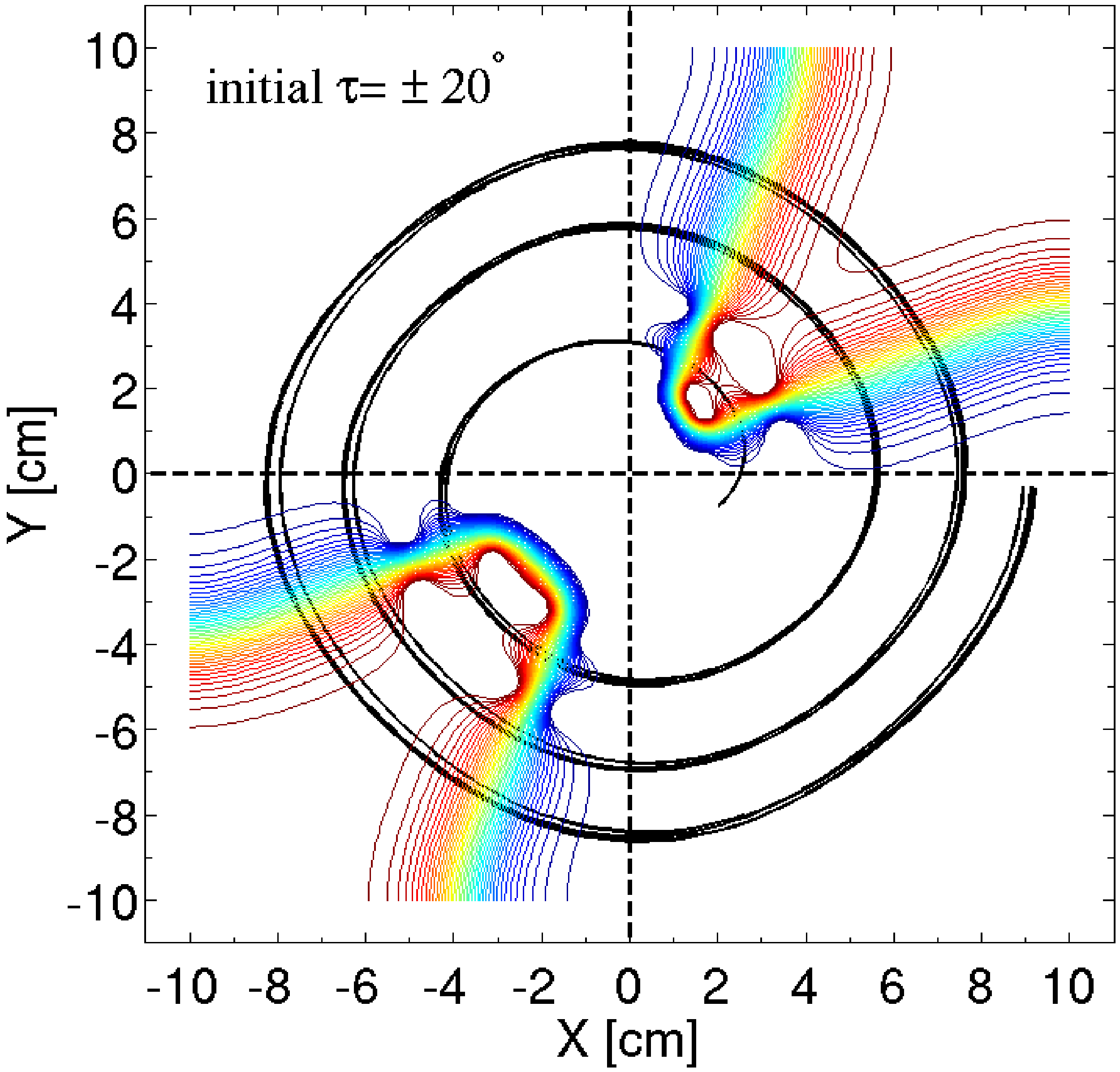
Tune diagram

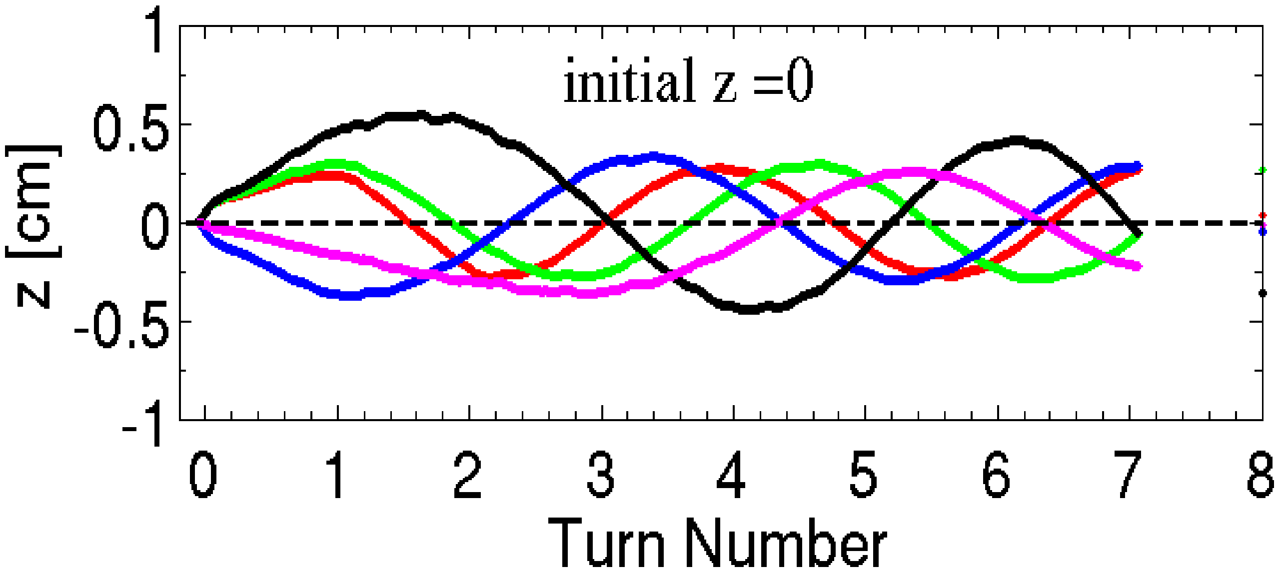
Coupling resonance
$\nu_r - \nu_z = 1$ is avoided.

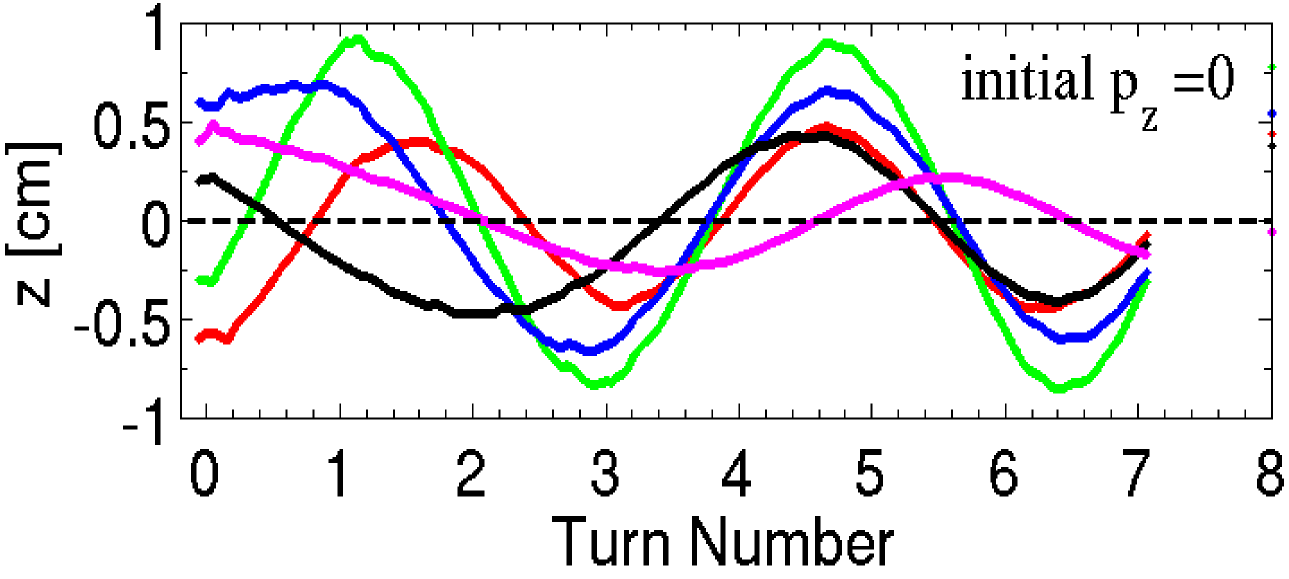
Half-integer resonance
$2\nu_z = 1$ occurs at
~147.2 MeV/n



Centre Region Orbits





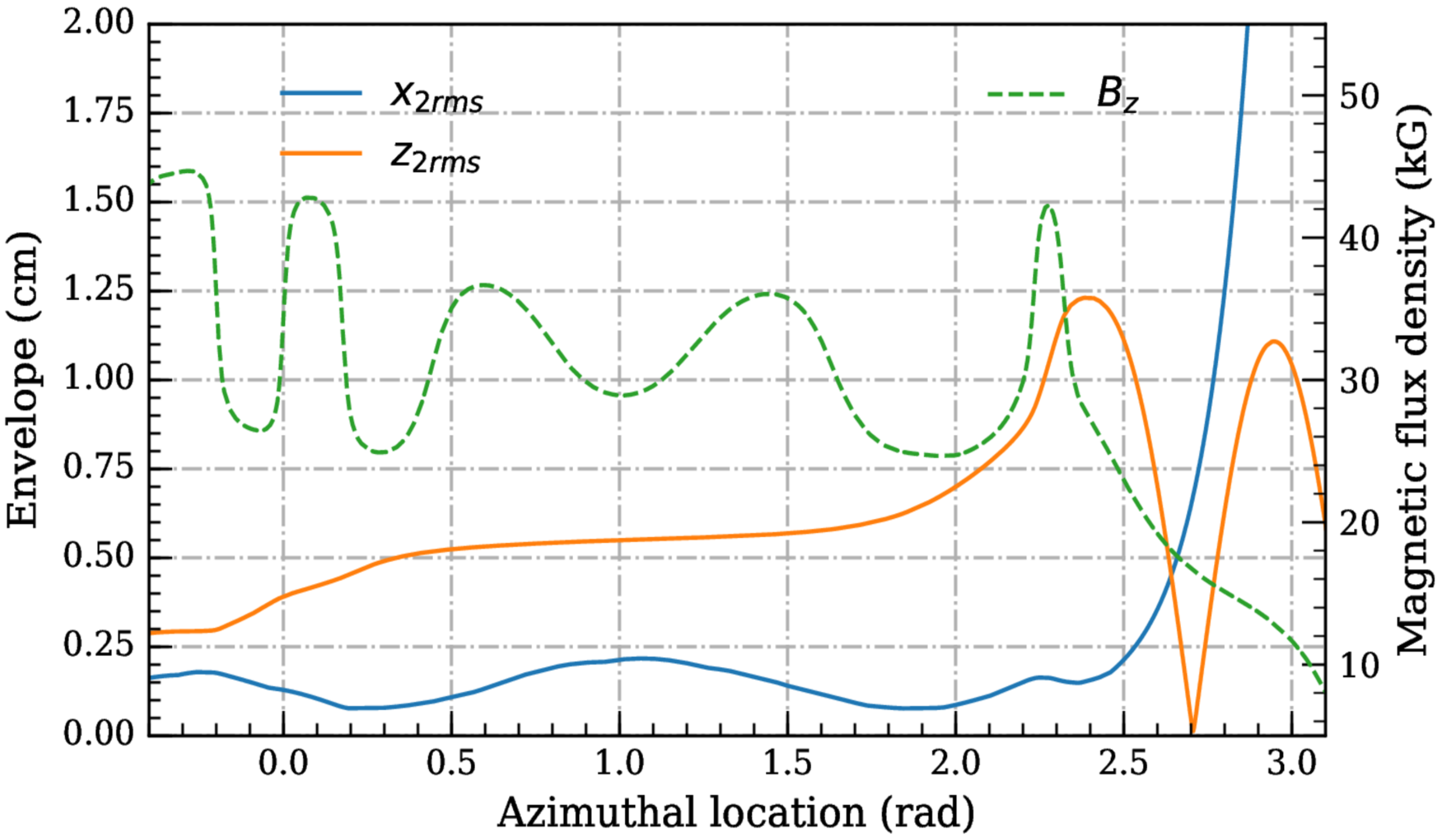


Beam Size at Extraction

Simulation of beam envelope along extraction trajectory
Circulating emittance:
0.54 π mm.mrad (4rms, normalized)

Axial beam size (orange),
Radial beam size (blue),
Magnetic field strength (green).

Magnetic channel is needed to pass through the fringe field.



Intensity Limitation

In both H_2^+ and H^- compact cyclotrons the space charge effects are strongest at the first turns.

The intensity limit is driven by:

- vertical space charge tune shift
- longitudinal space charge effect

TR30 demonstrated an upper limit of ~1.0 mA (with 5 mA injected dc beam).

For TR100+, current intensity limit scales to ~800 µA of extracted protons.

Beam Losses Constraints

Two predominant types of beam loss in TR100+:

- electromagnetic dissociation
- interactions with residual gas

- H_2^+ has binding energy of last electron of 2.75 eV, ~3.6 times larger than in H^- case. Unfortunately, the lowest electronic state of H_2^+ has 19 bound vibrational states. Ions in a vibrational state above 16 will dissociate during acceleration in the proposed configuration: ~1% of the beam could be lost.
- Vacuum has to be better than 1.0×10^{-7} Torr to maintain beam loss due to residual gas stripping below 1.0%.

Look Forward

Only preliminary conceptual consideration has taken place so far.

Next steps in the design effort:

- Injection line and center region optimization
- Sector's spiral shape optimizations for better vertical focusing
- Design of rf cavities to operate at high voltage and high power
- Exploration of vibrational states suppression in the ion source
- Superconducting coils design

Full scale project necessities:

- Converge on requirements/specifications
- Develop realistic schedule (~5 years)
- Secure funding
- Define and engage partners
- Build up dedicated project team

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Thank you
Merci

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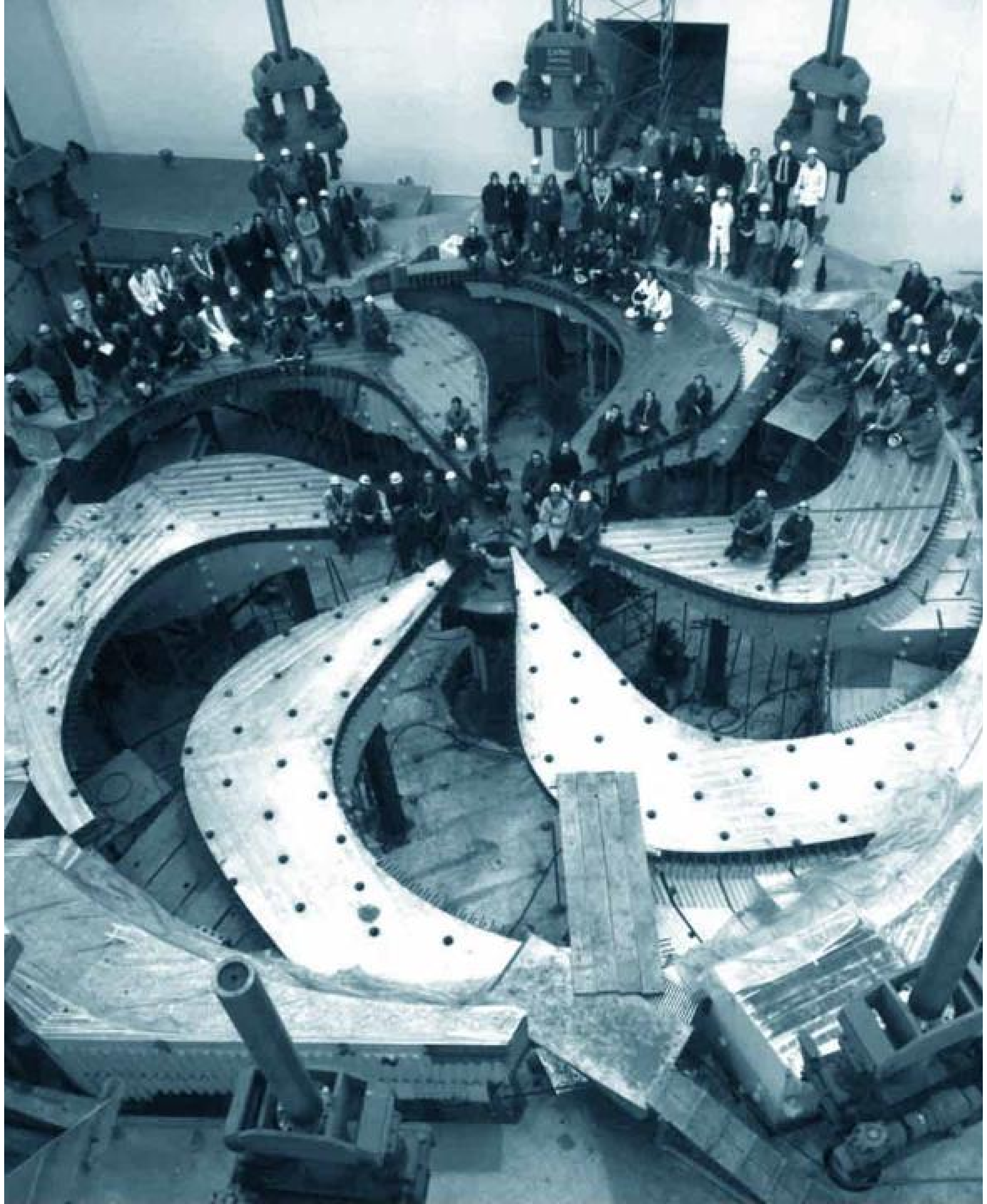

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